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An improved approach for measuring the tonic stretch reflex response of spastic muscles

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ABSTRACT

We propose a new method for detecting the onset of the stretch reflex response for assessment of spasticity based on the Tonic Stretch Reflex Threshold (TSRT). Our strategy relies on a three-stage approach to detect the onset of the reflex EMG activity: (i) Reduction of baseline activity by means of Empirical Mode Decomposition; (ii) Extraction of the complex envelope of the EMG signal by means of Hilbert Transform (HT) and; iii) A double threshold decision rule. Simulated and real EMG data were used to evaluate and compare our method (TSRT-EHD) against three other popular methods described in the literature to assess TSRT ('Kim', 'Ferreira' and 'Blanchette'). Four different groups of signals containing simulated evoked stretch reflex EMG activities were generated: groups A and B without spontaneous EMG activity at rest and signal-to-noise ratio (SNR) of 10 dB and 20 dB respectively; groups C and D with spontaneous EMG activity at rest, as observed frequently in spastic muscles, and SNR of 10 dB and 20 dB respectively. The results with simulated data showed a significantly higher accuracy of TSRT-EHD for detecting the onset of the reflex EMG activity in groups C and D when compared to the other methods. Analyses using real data from five post stroke spastic subjects demonstrated that the TSRTs generated by each method were dramatically different from one another. Nevertheless, only TSRT-EHD provided valid measures across all subjects.

1. Introduction

Spasticity is a common and complex phenomenon seen in neurologic disorders such as stroke, multiple sclerosis, spinal cord injury, traumatic brain injury and other central nervous system lesions [1]. The widely accepted definition of spasticity was proposed by Lance [2]: "spasticity is a motor disorder characterized by a velocity-dependent increase in tonic stretch reflexes with exaggerated tendon jerks, resulting from hyperexcitability of the stretch reflex, as one component of the upper motor neuron syndrome".

The clinical measurement of spasticity is essential for diagnosis and management of therapeutic interventions. However, quantifying spasticity is still a challenge and an unresolved problem, possibly due to the complexity and multifactorial nature of the phenomenon that can involve neural (central and peripheral) and non-neural factors (rheological properties of the muscles) [3].

Previous efforts to measure spasticity were focused on clinical scales such as the Ashworth Scale (AS) [4] and the Modified Ashworth Scale (MAS) [5], electrophysiological analysis [6], biomechanics methods using isokinetic dynamometers [7,8] or some other motor-driven devices [9,10]. However, there is no consensus regarding the use of a specific technique, mainly due to various limitations associated with each one of them. For instance, validity and reliability of clinical scales such as MAS or AS have been questioned, since they rely on the therapist's perception of the amount of resistance felt while performing a passive stretch of a spastic muscle to score muscle tone, and do not properly address the velocity dependent nature of the phenomenon [11]. Furthermore, these scales have been described as a grading of muscle stiffness that can only assess the resistance to passive movement and appear to be poorly related to the actual reflex muscle activity [12,13].

In an attempt to overcome those limitations, Levin and Feldman [14] proposed a method to quantify spasticity based on the indirect measurement of the so-called Tonic Stretch Reflex Threshold (TSRT). This measure is in close agreement with the traditional definition of spasticity proposed by Lance [2] and finds its basis in the motor control theory (lambda model), which states that the excitability of the Stretch Reflex Threshold (SRT) is highly related to central commands descend-

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ing to motoneurons [14,15]. Regulation of this threshold is intrinsically related to the supraspinal control and the excitability of the reflex activity. SRT (also referred to as Dynamic Stretch Reflex Threshold - DSRT) can be expressed by means of velocity and angular coordinates representing the joint angle at which motor neurons, and the respective muscles fibers, begin to be recruited in response to a stretch performed at a given velocity. Different velocities of stretch will result in different threshold measures – the higher the stretch velocity, the earlier would the evoked reflex response appear. In contrast, TSRT is a unique measure that represents the angle in which recruitment of motor neurons begins when the muscle is at rest (i.e., zero stretch velocity). Since a zero velocity stretch cannot be generated, TSRT must be inferred indirectly by linear regression over various DSRT points calculated at different velocities of stretch [16]. In other words, TSRT quantifies the minimum threshold of the reflex response within the biomechanical range of the joint of interest, and is expressed by the angular measure estimated for zero velocity by means of the DSRTs regression line. In so doing, TSRT may be used as a measure of spasticity, where values closer to full flexion of a joint (shorter muscle length) correspond to more severe cases, while values closer to full extension indicate minor levels of spasticity. It is also important to highlight that TSRT provides an entirely different metric to represent the clinical manifestations of spasticity. While standard tests such as AS and MAS grade muscle tone based on the amount of resistance felt by an examiner as the limb is moved through its range of motion to passively stretch specific muscle groups [5,6], TSRT provides a spatial measure indicating the angular range in which spasticity occurs.

TSRT was later proposed as a tool to evaluate spasticity as a result of stroke [16] and cerebral palsy in children [17]. The method used in those researches required a torque motor to promote passive stretches. The motor was controlled by position and velocity feedback. Although this is a valid strategy in a lab environment, it requires a costly and complex equipment to ensure the safety of patients. Over the years the protocol was revised by the researchers to incorporate manual stretches [12,18] and has been adopted by other groups for the development of TSRT measuring devices [19,20]. Such devices take simultaneous measures of the angular displacement and the electromyographic (EMG) activity, while manual passive stretches are performed at different velocities. The DSRTs can be calculated for each stretch as the angle at which the EMG reflex activity is detected – generally, a threshold level, defined as 2 standard deviations above the mean signal baseline collected at rest, is used [12,19]. However, great care must be taken when using simple thresholds, since minor errors in defining the exact moment when motor units begin to be recruited in response to the stretch can result in significant errors in the DSRTs, and consequently in the TSRT value. The main issue associated with methods to detect the EMG onset based on a simple threshold decision rule is the variability associated with different levels of signal-to-noise ratio (SNR). Generally, greater levels of noise will increase the value of the threshold and lead to a delayed detection of the onset [21]. To minimize this effect, Ferreira et al. [20] proposed a method to calculate the DSRTs based on a double threshold strategy for EMG onset detection developed by Xu and Adler [22]. The method analyses the EMG power in segments and uses the minimum and maximum values obtained out of all segments to estimate the noise power and the signal to noise ratio, which are then used it to define the probability of each sample of the signal be part of an active contraction or muscle tone. In order to reduce the occurrence of false positives and false negatives, the method applies a second threshold on segments of 200 ms. A segment is said to contain an active contraction (reflex) if at least 50% of its samples are 'active'. The authors report an improvement of muscle activation detection in moderate to severe spastic conditions in 23% of their database. This relatively modest improvement may be the result of imprecisions in the method, caused by the necessary tradeoff between statistical detection and time resolution, as reported by Xu and Adler [22] – the larger the segment, the lower the time resolution. This may have had an important impact in the final TSRT values calculated by their method, as it can be inferred by the many linear regressions with very low coefficients of determination obtained in their experiments (R^2 as low as 0.02).

A review of the literature shows several other threshold-based and statistically optimized algorithms to detect the onset of EMG activity evoked by a stimulus [21,23–25]. However, most of them are only truly reliable for good quality signals, with marked differences between rest and contraction – and that would not be necessarily the case in data collected during stretching of spastic muscles. Disturbances in the firing rate modulation of motor neurons are prevalent in spastic muscles after stroke and prolonged spontaneous motor unit discharges are common at rest and following voluntary or reflex muscle activation [26–28]. This can result in increased background EMG activity at rest. In this case, traditional band-pass (or stop-band) filtering, generally used to enhance the signal-to-noise ratio and improve threshold detection, would not work.

In this paper we propose a novel three-stage approach to properly detect the onset of the reflex EMG activity for TSRT measurement: (i) Reduction of baseline activity by means of Empirical Mode Decomposition (EMD); (ii) Extraction of the complex envelope of the EMG signal based on Hilbert Transform (HT) and; iii) A double threshold decision rule.

We hypothesize that the use of a detection strategy combining these three elements (EMD, Hilbert envelop and double-threshold) might provide a better performance in detecting the onset of the stretch reflex with direct impact in the correct definition of TSRT of spastic muscles. We believe that EMD can be especially useful for distinguishing the reflex EMG activity from baseline EMG containing spontaneous motor unit discharges. This paper will address this hypothesis by presenting our procedure and evaluating its performance against other methods described in the literature for TSRT measurement.

2. Methods

The basic steps for measuring TSRT were described by Jobin and Levin [17]. The procedure currently consists on the therapist performing several (n) manual passive stretches at different velocities while EMG and angular measures are simultaneously taken. The joint angular velocity (φ [°/s]) is derived from the angular measures (θ [°]): $\varphi = d\theta/dt$. The time (onset – τ_i [s]) at which muscles fibers begin to be recruited in response to each stretch (i) is measured by means of some algorithm to process the EMG signal. The angular velocities(φ_i) and the joint angles (θ_i) at each onset (τ_i) are taken and form a set of n DSRT pairs ($DSRT_i = (\theta_i, \varphi_i)$), which are then used to compute TSRT (excitability of motoneurons at 0°/s), generally, by means of linear regression. As described earlier, a crucial step is the correct measurement of τ_i, since any error at this point is propagated throughout the process and may generate incorrect TSRT measures. In this section we present our method to improve the accuracy for detecting τ_i and, as a consequence, the accuracy of TSRT.

2.1. An EMD based strategy for the detection of the reflex response of spastic muscles

Our method can be expressed by three main units: (i) Reduction of baseline activity by means of Empirical Mode Decomposition (EMD); (ii) Extraction of the complex envelope of the EMG signal based on Hilbert Transform (HT) and; iii) A double threshold decision rule. Hereafter, we will refer to this method as TSRT-EHD (EMD/HT/Double Threshold based TSRT).

- *Stage 1 – Reduction of baseline activity*

EMD is a technique that decomposes any temporal series into a series of oscillatory time-scaled components called Intrinsic Mode